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Potential of photovoltaic systems in countries with high solar irradiation

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ABSTRACT

Renewable energy sources derived principally from solar energy have been gaining ground over the last few years and are now beginning to contribute to the global energy mix. Solar energy in the form of direct electricity conversion (photovoltaics) is already very popular in countries such as the United States, Germany and Japan. The enormous potential of photovoltaic (PV) technology is also obvious and favourable in countries with high irradiation such as the Mediterranean region. The objective of this paper is to review the different up and coming PV technologies, to explore the potential of different PV systems in countries with high solar irradiation and to compare their performance through the assessment of thirteen different types of PV systems that have been installed side by side in Nicosia, Cyprus and Stuttgart, Germany. Finally useful insight into the performance of the PV systems as a function of the meteorological conditions and location will be highlighted.

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1. Introduction

The PV technology sector is a fast growing industry which has shown a worldwide increase with European installed capacity reaching 4689 MW_p in 2007 [1] (Photon data of April 2009: 4279 MW_p in 2007 and 7910 MW_p in 2008 [2]) and proving in this way its ability for future development. In its recent prediction (September 2008) the European PV Industry Association (EPIA) estimates that PV could provide 12% of the European electricity consumption by 2020, highlighting its potential [3]. Amongst the European countries, Germany has been and continues to be the European PV market leader with the highest installed capacity. The

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enormous prospects and job opportunities that have been created due to this technology in Germany has led the way for upcoming markets such as Spain and Italy with even more favourable climatic conditions. In general the Mediterranean region is an area of strategic importance for PV markets and can potentially play an important part in the integration and uptake of this technology.

In particular, solar irradiation in Cyprus (a typical example of an island in the Mediterranean sunbelt) is one of the highest in Europe, with more than 300 days of the year considered as having sunny weather and an annual irradiation of around 2000 kWh/m^2 on a tilted surface of 27.5°, which is much higher than the sunniest areas of the world's largest market, Germany [4]. The high solar resource of such countries clearly suggests that photovoltaic technology can have a major impact and potential as an alternative energy source in the quest for combating climate change and reducing emissions.

In order to gain ground over conventional electricity prices, PV technologies need to overcome the key commercial challenge of high initial cost. The high cost is directly affected by the system cost, performance and operating lifetime. Currently crystalline silicon solar modules are more expensive than thin film ones, which are less efficient but are usually also integrated into building materials [5]. Important cost reductions are expected to arise mainly through the improvement of manufacturing techniques for crystalline technologies, the emergence of new PV technologies such as thin film and concentrator technologies as well as the reduction in manufacturing prices as a result of the creation of economies of scale due to the increased demand for deployment.

This paper provides a review of all the current and up and coming PV technologies. Furthermore, the potential of PV technology in countries of high solar irradiation such as the Mediterranean region is demonstrated through the side-by-side performance evaluation of thirteen different PV technologies installed both in Nicosia, Cyprus and Stuttgart, Germany. More specifically, the outcome of this work provides information on the performance of the different PV technologies at the two test sites which is valuable when assessing the different technologies. Finally, the high solar resource and high energy yield shown by all systems in Cyprus prove the enormous potential that this technology demonstrates in regions of high solar irradiance such as the Mediterranean region.

2. Photovoltaic technologies

Even though commercial PV modules are available and being widely deployed, it is essential that more research is carried out to improve their cost-effectiveness and performance and target well known issues to increase their competitiveness. Different PV technologies have demonstrated substantial improvements and transformations over the past 40 years and are expected to undergo developments in the following decades [6]. The drive for more PV installations is strengthening and this is creating widespread opportunities for business growth and a market with massive job potential. Market and research analysts estimate that in the near future crystalline PV modules will continue to dominate this market segment due to the fact that in most installation cases, limitations on the available area necessitate the use of modules with high efficiencies. However once the first thin film modules with efficiencies up to 10% become commercially available, which was achieved in 2008, then many mono-crystalline modules with low efficiency will come under pressure in maintaining their market share. The expected development of PV technology over the coming decades is shown in Table 1 [6].

The highest PV module efficiencies obtained from a survey undertaken by the National Renewable Energy Laboratory (NREL), USA, on commercial flat-plate manufacturers' websites in April 2008 are listed in Table 2 [7].

Table 1
Expected development of PV technology over the coming decades [6].

Description	2020	2030	Long term potential
Typical turn-key system price (€/W excl VAT)	2.5/2.0	1	0.5
Typical electricity generation costs southern Europe (€/kWh)	0.15/0.12	0.06	0.03
Typical commercial flat-plate module efficiencies	Up to 20%	Up to 25%	Up to 40%
Typical commercial concentrator module efficiencies	Up to 30%	Up to 40%	Up to 60%

Table 2
Module efficiencies from NREL survey of manufacturers' websites [7].

Module	Technology	Efficiency (%)
SunPower 315	Mono-Si, special junction (sp. j.)	19.3
Sanyo HIP-205BAE	CZ-Si, "HIT," sp. j.	17.4
BP7190	CZ-Si, sp. j.	15.1
Kyocera KC200GHT-2	MC-Si, standard junction (std. j.)	14.2
Solar World SW 185	CZ-Si, std. j.	14.2
BP SX3200	MC-Si, std. j.	14.2
Suntech STP 260S-24V/b	MC or CZ-Si, std. j.	13.4
Solar World SW 225	MC-Si, std. j.	13.4
Evergreen Solar ES 195	String-ribbon-Si std. j.	13.1
WürthSolar WS11007/80	CIGS	11.0
First Solar FS-275	CdTe	10.4
Sharp NA-901-WP	a-Si/nc-Si	8.5
GSE Solar GSE120-W	CIGS	8.1
Mitsubishi Heavy MA100	a-Si, single-junction	6.3
Uni-Solar PVL136	a-Si, triple junction	6.3
Kaneka T-SC(EC)-120	a-Si single junction	6.3
Schott Solar ASI-TM86	a-Si/a-Si same bandgap tandem	5.9
EPV EPV-42	a-Si/a-Si same bandgap tandem	5.3

It is clear that PV technologies are rapidly developing and emerging and that there is a diverse portfolio of such technologies which is going to threaten the domination of crystalline silicon (c-Si) in the near future. Below a review of the different up and coming technologies is given followed by a comparison of these different technologies installed side by side at two locations in Nicosia, Cyprus and Stuttgart, Germany.

2.1. Crystalline technologies

The preferred economic choice for grid-connected applications at the moment is crystal-based silicon PV as already some manufactures such as SunPower offer solar cells with efficiencies of 20% (non-concentrating) [8]. Such efficiencies are the highest amongst all other market technology based PV modules. Crystalline silicon has an ordered crystal structure, with each atom ideally lying in a pre-determined position. Mono-crystalline technologies exhibit predictable and uniform behaviour, are highly efficient but are the most expensive type of silicon because the manufacturing processes are slow, require highly skilled operators and are labour and energy intensive.

Until recently the majority of solar cells were made from pure mono-crystalline silicon produced for the semiconductor industry, having no impurities or defects in its lattice. This has been a time consuming and expensive manufacturing methodology and produced silicon of a higher purity than required for PV cells. A number of approaches to reduce costs of crystalline PV cells and modules have therefore been under development. Techniques for the production of multi-crystalline silicon are simpler and therefore cheaper than those required for mono-crystalline material. However, the material quality of multi-crystalline is lower than that of mono-crystalline material due to the presence of grain boundaries.

The shortage and high prices of polycrystalline silicon have also been the main reasons for many solar cell manufacturers to seek alternative raw materials such as metallurgical-grade silicon (mg-Si) which is successfully entering the PV arena.

Special manufacturing techniques have been adopted by PV companies such as the Sanyo hetero-junction with intrinsic thin film (HIT) and the SunPower back-contact cells that led the way for increased efficiencies. Recently an efficiency of 21.5% for an HIT cell of size 100.3 cm^2 has been reported and confirmed by the Advanced Industrial Science and Technology Institute (AIST) [9]. Silicon material from PV modules can also be removed and recycled to produce solar cells again with acceptable performance [10].

2.2. Thin film technologies

The advantages of thin films over crystalline cells have been the important driver to initiate a PV market in this area. Thin film module production manufacturing processes operate at a much lower temperature than that of crystalline silicon and this reduces the embodied energy per watt-peak. Another manufacturing advantage is the fact that PV films can be easily deposited on a wide variety of both rigid and flexible substrates including glass, steel and plastics. However, thin film technologies show significant initial performance degradation when deployed outdoors (Staebler-Wronski effect [11]) and the most important challenge of thin film technologies remains the production improvement of the technology so as to increase the efficiency of industrially produced cells.

Initial products of this technology were made from very thin films of silicon in a form known as amorphous silicon (a-Si) and there has been a growing interest in this technology due to its promise of low production costs and the fact that conditions for preparing a-Si are even less critical, in principle, than those for preparing polycrystalline silicon [12]. Amorphous silicon cells should be cheaper to produce than those made from crystalline silicon and are better light absorbers, facilitating in this way thinner and therefore cheaper cells. However, stabilised amorphous silicon efficiencies of the best commercial modules remain low at 6–7% [7].

Amorphous silicon is by no means the only material suited to thin film technologies. Amongst the many other possible thin film technologies some of the most promising are those based on compound semiconductors in particular Copper–Indium–Diselenide (CIS), Copper–Gallium–Diselenide (CGS), Copper–Indium–Gallium–Diselenide (CIGS), and Cadmium Telluride (CdTe) with the major technical progress particularly for those based on CdTe and CIGS [13]. More specifically, several II-VI chalcopyrite compounds and their mixed compounds were found to be very suitable for photovoltaic applications. The most important of them are CIS, CGS and CIGS. Currently, the highest efficiency has been reported to be 19.9% with CIGS solar cells that were developed at NREL, USA, while the highest aperture-area conversion efficiency of 13% for a CIGS power module has been achieved by Würth Solar in Germany [14]. There are a variety of different production deposition methods for the fabrication of absorber films. The main production techniques for this technology are co-evaporation and reactive annealing of metal precursor films. Other methods include non-vacuum techniques like electrodeposition. Manufacturing plants with a total production capacity of about 20 MW are already in operation in Germany [15].

Another front runner of thin film solar PV technology is CdTe, due to its stability and chemical simplicity. CdTe is a direct band gap II-VI semiconductor with an optical band gap of 1.44 eV, which is close to the optimum for photo-conversion. A disadvantage of using CdTe and most of the II-VI semiconductors is the difficulty in electronic doping and specifically controlling the doping concentration in p-type CdTe. Furthermore, the toxic nature of cadmium and the environmental consequences of deploying large solar systems based on toxic materials have caused serious concerns which are currently being carefully examined, even though the trace amounts of this material in a thin film PV module do not approach toxic limits. The most efficient CdTe cell has been reported with an efficiency of 16.5%, demonstrated and confirmed by NREL [16].

2.3. III-V single and multi-junction technologies

A promising approach for achieving better efficiencies is through utilising greater portions of the solar spectrum. One method for achieving this is by combining cells of different band gaps in a tandem arrangement. A single junction cell can provide theoretical efficiencies of 30% while as the number of junctions increases from 1 to infinity, the thermal loss due to absorption of light with energy greater than the band gap goes to zero, resulting in a thermodynamic performance limit of 68% [17] and for sunlight of full concentration, the new limit is above 85% [18]. Ultra high efficiency multi-junction solar cells have therefore attracted a lot of attention [19].

More specifically, III-V solar cells have become the standard technology for space power generation, mainly due to their high efficiency, reliability and ability to be integrated into very lightweight panels. The new emerging types of space solar cells are continually increasing in performance and it is expected that commercial multi-junction solar cells with 30% conversion efficiency under the AM 0 space spectrum will appear in the near future [20].

A number of techniques have been developed to produce multi-junction solar cells. These cells are mechanically stacked, monolithically integrated or created through a combination of both techniques. Mechanically stacked techniques have led to dual junction cells based on Gallium Arsenide (GaAs) reaching efficiencies well above 31% and recently researchers at the Fraunhofer Institute for Solar Energy Systems (ISE) have achieved a record efficiency of 41.1% for the conversion of sunlight into electricity by concentrating sunlight by a factor of 454 onto a small 5 mm^2 multi-junction solar cell of GaInP/GaInAs/Ge (Gallium Indium Phosphide, Gallium Indium Arsenide on a Germanium substrate) [21].

The use of GaAs as a solar cell material has also the disadvantage of the limited Gallium resources which dictates that GaAs will always be an expensive material. This is offset by the fact that GaAs cells are ideal for use in systems that concentrate light, thus the amount of material required for a given power output is reduced.

2.4. Concentrator technologies

An emerging application of PV devices is in concentrator photovoltaic (CPV) systems. These systems are rapidly gaining in popularity as they offer several economic advantages over existing technologies. CPV systems make use of relatively inexpensive optical devices, such as lenses or mirrors to focus light from an aperture onto a smaller active area of semiconductor material. In doing so, light is 'concentrated' to higher intensities than ordinary sunlight, and less PV cell material is required for a given output. This brings several benefits: the total cost of the system can be reduced; higher system efficiencies are possible due to the increased solar flux intensities and because higher efficiency cells can be used without incurring great cost; demand for semiconductor materials can be reduced, thereby easing supply restrictions on these materials and facilitating reductions in market price.

Although Sandia is credited with constructing the first terrestrial CPV system in 1977, the fall in cost of energy from

fossil fuels in the 1980s arrested the development of the technology. However, recent years have seen a rise in the price of conventional fossil fuels and concern over the protection of the environment and this has led to renewed interest in the potential of CPV. Modern CPV systems like their predecessor, the SANDIA I, predominantly use Fresnel lenses to concentrate light onto PV cells. Geometric concentration factors range from less than 2$\times$ ('times concentration') to upwards of 500$\times$, reflecting the diverse number of approaches under development. Low-to-medium concentration systems (below 100$\times$) often employ cheaper cells, such as adapted c-Si cells since these are more economically viable at these levels. High concentration systems (>100$\times$) use more expensive multi-junction technologies, such as III-V cells, to achieve higher efficiencies, but are expected to remain economical due to the small amounts of cell area required [22].

Although CPV offers a promising route to lower solar electricity prices, it remains a strong technical challenge. Systems operating above 5$\times$ require some form of solar tracking. Often CPV systems require highly accurate tracking, which contributes significantly to the cost of the system, and reduces performance reliability. Also, as yet there is little long term experience of CPV systems in operation and therefore the cost of electricity produced over the system lifetime is hard to predict. It is expected that very high efficiency concentrating systems will increase their competitiveness when concentrator module efficiencies reach the 30% mark. Currently, Concentrix Solar have reported concentrator AC system efficiencies of 23% in May 2008 [23].

2.5. Building integrated PV (BIPV) technologies

The recent rapid expansion in installed photovoltaic capacity is largely due to the increase in grid-connected photovoltaic systems mounted on buildings. The term 'building integrated' refers to PV systems that constitute part of a building envelope, but has also been used to describe systems that are simply mounted on the rooftop of buildings. For this reason, it is best to describe BIPV as systems that are readily integrated with the physical building or with the building's grid connection. The integration of such systems usually requires the advice of professional civil engineers, architects and PV system designers during the design of the system and the building. In this case a good evaluation of the installation site is required so as to maximise solar coverage and electricity output. BIPV are usually installed on facades, building window systems and as flexible rolls on roofs. Consequently, BIPV systems often have restricted views of the sun, and their orientation must be optimised for the particular circumstances of their installation site [24].

BIPV technologies can achieve significant cost reductions when they are used as part of the building envelope and thereby offset the cost of the building materials they replace. Many modern exterior claddings can have costs per square meter comparable to the price of PV modules. At the leading edge of BIPV are the three main thin film photovoltaic technologies (a-Si, CdTe and CIGS) which are at present commercially available. The most important issues for the successful integration of thin film BIPV technologies include gaining experience on the design and operation of such systems as well as acquiring knowledge of their life-cycle costs.

Apart form thin film BIPV, concentrator photovoltaic systems designed for building integration have also been gaining ground. These systems often work at low and medium concentration levels if installed on the rooftop of a building. Low concentration levels are preferred for integration into facades since direct views of the sun are restricted and the diffuse component of light represents a larger proportion of the total irradiation available in such cases. Indeed, restrictions in the availability of direct light has led to many designs of building integrated concentrators that utilise the passive benefits of building integration, such as solar gain control, interior light distribution and collection of thermal energy for pre-heating of water in order to increase total system efficiency and cost-effectiveness [25].

Even though there are at the moment a number of innovative ideas and designs for such technologies, the field of BIPV still has room for improvement. Research into the complex interaction between the building envelope and BIPV is still required, since the inclusion of such systems can affect the solar gain of buildings as well as the thermal conductivity of the areas where it is installed.

2.6. Emerging and new PV technologies

The development of new PV technologies is the subject of numerous research activities worldwide; the target of which is the lowering of costs and the increase of conversion efficiency. New device technologies include organic, dye sensitised, quantum well solar cells and in general nanostructured materials for solar energy conversion. PV technologies in this category can be distinguished mainly through the approaches taken to tailor the properties of the active layer to better match the solar spectrum and approaches that modify the incoming solar spectrum and function at the periphery of the active device.

A different concept to the existing solar cell approach has emerged with the inclusion of organic solar cells in the field of PV. Organic photovoltaics comprise of electron donor and electron acceptor materials rather than semiconductor p–n junctions and are characterised either as hybrid when organic solar cells retain an inorganic component or fully organic. It is essential that both hybrid and fully organic solar cells are made more stable and that their efficiency increases to the 15% target for laboratory cells by 2015, if this technology is to have potential in the future [6].

Nanostructure use in photovoltaic devices has attracted major interest with dye sensitised photoelectrochemical solar cells (DSSC) based on nanoporous titanium dioxide which is the best representative of the family of nanostructured PV devices [26]. These solar cells have been widely investigated during the past decade and an efficiency of 10.4% was achieved by O'Regan and Gratzel [27]. This technology can prove extremely important in the establishment of new designs that reduce the production cost of photovoltaic devices, because it is made of low cost materials and does not need elaborate apparatus to manufacture.

Another important novel alternative in PV is the quantum well solar cell (QWSC). Unlike multi-junction solar cells, these are created by growing simple quantum wells of a smaller band gap material within the space charge region of p–n or p–i–n structures [28]. The idea behind this technology is to facilitate the ability to absorb light of energy below the bulk band gap energy. These solar cells are fabricated by either molecular beam epitaxy or metal organic chemical vapour deposition. QWSC tends to increase short circuit current, open circuit voltage and in general the efficiency of solar devices. At present the outcome of band gap engineering of InGaPs/GaAs solar cells using strain balanced quantum wells has been an efficiency of 30.6% under 54 suns AM 1.5 [29].

3. Performance evaluation of different PV technologies under the same climatic conditions

Knowledge of the outdoor performance of PV technologies is an essential requirement for their successful application and towards the development of new technologies in the quest for lower electricity prices. The performance, reliability, stability and degradation assessment of different PV technologies under real operating conditions constitute crucial parameters for the assessment of these technologies. The next section describes such an effort which has been funded by the German Federal Ministry for

Fig. 1. Photovoltaic systems installed at the University of Cyprus, Nicosia, Cyprus.

the Environment, Nature Conservation and Nuclear Safety (BMU) in order to allow field studies to be undertaken and to enable direct comparisons of different technologies under identical conditions to be carried out.

Thirteen grid-connected PV systems of nominal power 1 kW_p each have been installed in Nicosia, Cyprus and Stuttgart, Germany (see Figs. 1 and 2) providing the opportunity for direct comparisons under the different climatic conditions of the two countries. More specifically, the installed PV technologies in Nicosia, Cyprus consist of twelve fixed plate mounted systems, a two-axis tracking system and a flatcon concentrator system. The systems range from mono-crystalline, multi-crystalline silicon to amorphous silicon, CdTe, CIGS, HIT-cell and other solar cell technologies from a range of manufacturers such as Atersa, BP Solar, Mitsubishi, Sanyo, Solon, SunPower, etc. The PV modules are mounted on mounting racks at the optimal inclination to provide maximum annual yield for each respective location.

Table 3 provides a detailed description of the installed systems.

Within the scope of the performance comparison between the systems it is very important to emphasise that a consumer must also consider the size (surface area) and price of each system so as to decide which is more suitable. Information on the size of each 1 kW_p system and their respective efficiencies is summarized in Table 4.

Fig. 2. Photovoltaic systems installed at the *ipe* Stuttgart, Germany.

Table 3
Installed PV technologies at the two test sites.

Manufacturer	Module type	Technology
Atersa	A-170M 24V tracked	Mono-crystalline silicon
Atersa	A-170M 24V	Mono-crystalline silicon
BP Solar	BP7185S	Mono-crystalline silicon (Saturn-cell)
Sanyo	HIP-205NHE1	Mono-crystalline silicon (HIT-cell)
Suntechnics	STM 200 FW	Mono-crystalline silicon (back contact-cell)
Schott Solar	ASE-165-GT-FT/MC	Multi-crystalline silicon (MAIN-cell)
Schott Solar	ASE-260-DG-FT	Multi-crystalline EFG silicon
SolarWorld	SW165 poly	Multi-crystalline silicon
Solon	P220/6+	Multi-crystalline silicon
Mitsubishi	MA100T2	Amorphous silicon (single cell)
Schott Solar	ASIOPAK-30-SG	Amorphous silicon (tandem cell)
First Solar	FS60	Cadmium Telluride
Würth	WS 11007/75	Copper–Indium–Gallium–Diselenide

Table 4
Information for installed PV systems.

PV technology	System power (W_p)	Size (m^2)	Module efficiency nameplate (%)
Atersa mono-c-SI tracker	1020	7.90	12.9
Atersa mono-c-SI	1020	7.90	12.9
BP mono-c-Si	1110	7.52	14.8
Sanyo HIT-Si	1025	6.26	16.4
Suntechnics mono-c-Si	1000	6.22	16.1
Schott MAIN-Si	1020	7.87	13.0
Schott EFG-Si	1000	8.58	11.7
SolarWorld multi-c-Si	990	7.82	12.7
Solon multi-c-Si	1540	11.50	13.4
Mitsubishi a-Si	1000	15.74	6.4
Schott Solar a-Si	960	18.00	5.4
Würth CIGS	900	8.75	10.3
First Solar CdTe	1080	12.96	8.3

3.1. Measurement system description

Both climatic data and PV system measurements are acquired from the test facilities and stored through an advanced measurement platform. The platform comprises of meteorological and electrical sensors connected to a central data logging system that stores data at a resolution of 1 s. The monitored meteorological data include the global irradiation at the plane of array (POA), wind direction and speed as well as ambient and module temperature. The electrical parameters measured include DC current and voltage, DC and AC power at maximum power point (MPP) as obtained at each PV array output. All the installed acquisition devices are shown in Table 5.

The PV systems at both sites have been monitored from the beginning of June 2006 and currently the second year of evaluation has been completed.

Table 5
Installed data acquisition equipment and sensors at both test sites.

Parameter	Manufacturer	Model
Data acquisition	Delphin	Topmessage
Temperature ambient	Theodor Friedrich	2030
Temperature module	Heraeus	PT 100
Global irradiance	Kipp Zonen	CM 21–CV 2
Direct normal irradiance (DNI)	Kipp Zonen	CH 1
DC voltage	Custom made	Potential divider
DC current	Custom made	Shunt resistor
DC power	Delphin	Topmessage
AC power	NZR	AAD1D5F
Wind speed	Theodor Friedrich	4034
Wind direction	Theodor Friedrich	4122

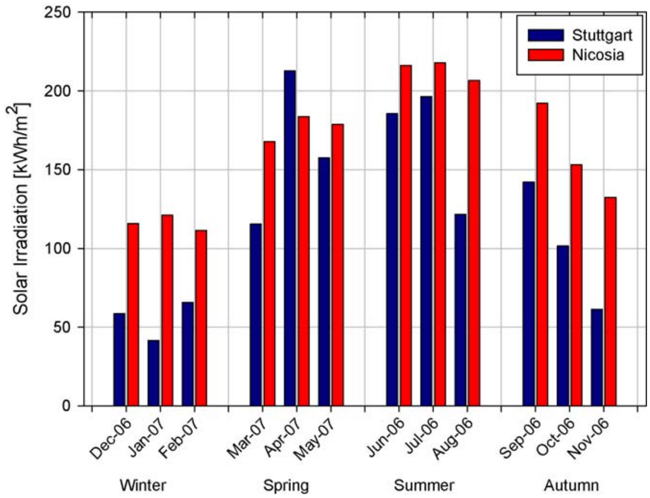

Fig. 3. Solar irradiation in the POA as measured by the pyranometers installed both in Nicosia and Stuttgart.

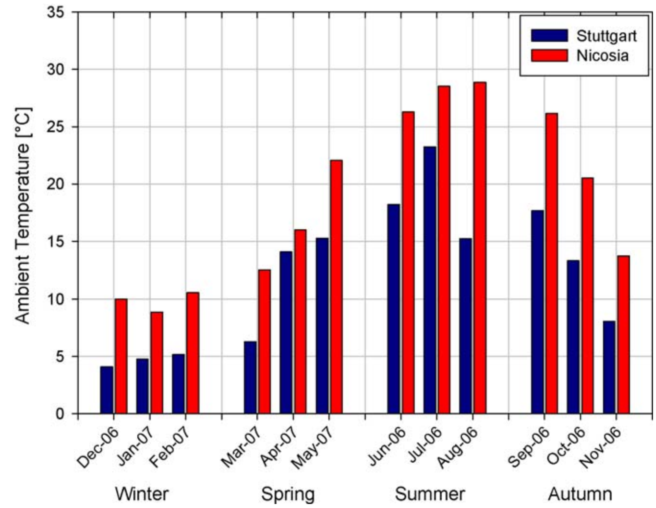

Fig. 4. Ambient monthly average temperature measured both in Nicosia and Stuttgart.

4. Results

4.1. Solar resource

PV modules installed in Cyprus are subject to high irradiation which favours their performance but also to high module temperatures reaching 60 °C in the summer. The annual solar irradiation measured on-site in Cyprus using the pyranometer installed in the POA was found to be 1997 kWh/m^2, with the maximum contribution occurring during the summer period. Lower annual irradiation for the same time period has been measured by the same type of pyranometer in Stuttgart with annual irradiation of 1460 kWh/m^2 and highest irradiance shown in April (see Fig. 3).

As it is essential to avoid uncertainty in measurements obtained from only one source (the central pyranometer) a number of silicon solar radiation sensors have been further spread over the field to detect inhomogeneous irradiation, which could be caused by obstacles afar. At both locations the measured deviation between the silicon solar cell sensors was very small (approximately 1%) ensuring the validity of the measured results.

A comparison of average daily ambient temperatures has also shown that in Cyprus a maximum average ambient temperature of 29 °C in the summer and minimum of 9 °C during the winter is obtained. The climatic conditions were different in Stuttgart as the observed ambient temperatures reached maximum averages of 23 °C in July and respective minimum temperatures of 4 °C in December (see Fig. 4) [30].

Furthermore, the suitability of CPV for contributing to the energy balance of Cyprus is indicated by the DNI component that is over 70% of the global irradiance for a typical day (01/06/2007) in the summer (see Fig. 5).

4.2. Solar energy production in Cyprus

Most installed PV systems produced annual ac energy yields within the range of 1600–1700 kWh/kW$_p$ with the values normalised to kW$_p$ with the nameplate power (see Fig. 6). For the same period of time, the tracker has shown an ac energy yield of 2039 kWh/kW$_p$ and dc energy yield of 2236 kWh/kW$_p$, showing 30% higher ac energy yield over the average fixed plate energy yield for the same period [31].

The highest annual energy yield was obtained by the SunPower mono-crystalline Silicon, Sanyo HIT, CIGS and CdTe systems. The highest monthly energy yield was obtained during the summer

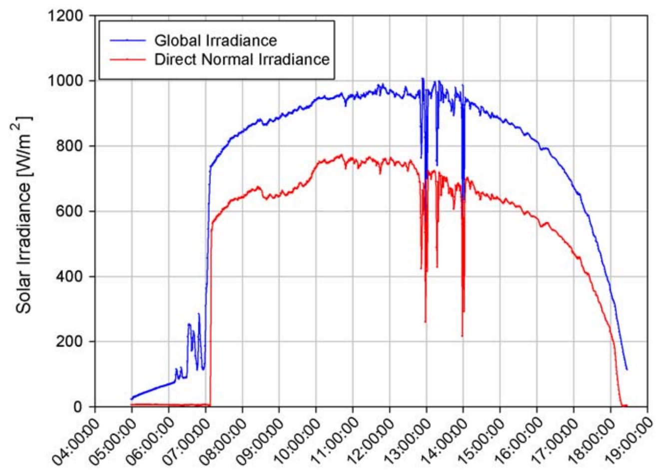

Fig. 5. Variation of global irradiance and DNI for a typical summer day (01/06/2007) in Nicosia, Cyprus.

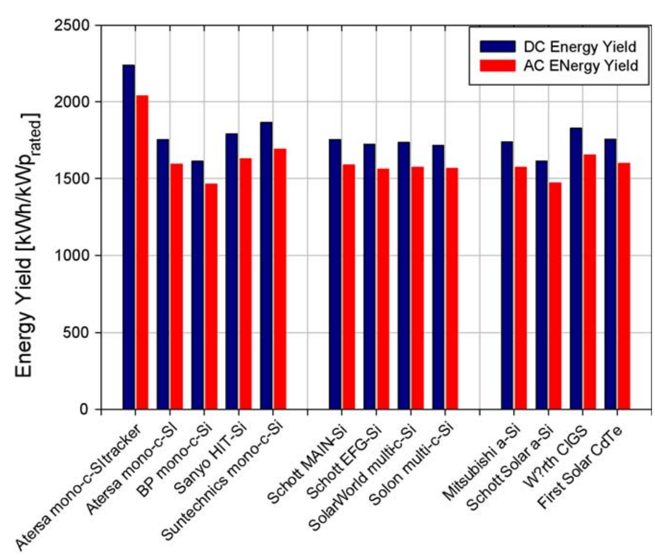

Fig. 6. Energy yield (dc) and (ac) of the installed systems in Nicosia in the time period June 2006–2007. The values are normalised to kW$_p$ with the nameplate power.

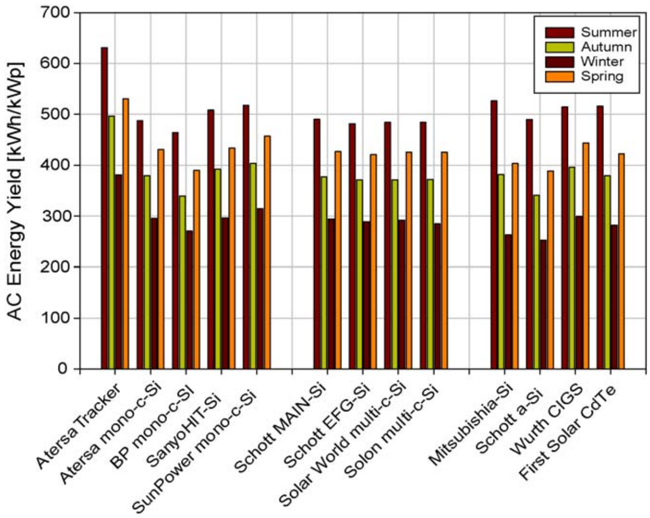

Fig. 7. Energy yield (ac) of the installed systems in Nicosia for the four seasons in the time period June 2006–2007 (summer: 01/06/2006 to 31/08/2006, autumn: 01/09/2006 to 30/11/2006, winter: 01/12/2006 to 28/02/2007 and spring: 01/03/2007 to 31/05/2007). The values are normalised to kW_p with the nameplate power.

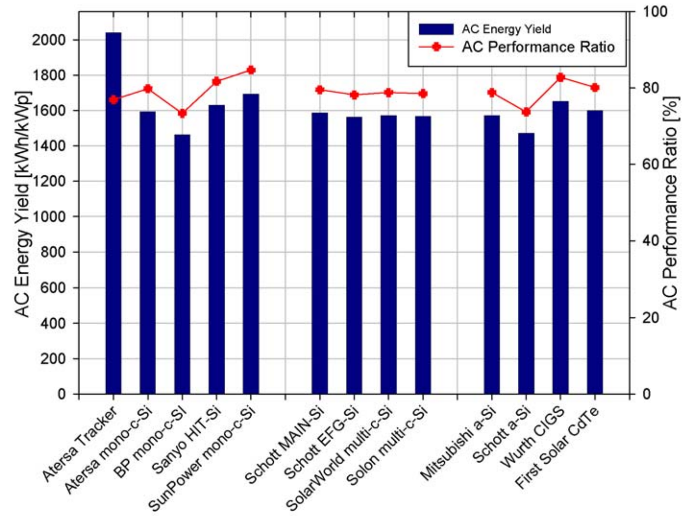

Fig. 8. Energy yield (ac) and performance ratio (ac) of the installed systems in Nicosia in the time period June 2006–2007. The values are normalised to kW_p with the nameplate power.

months with June providing the highest ac yield of 168 kWh/kW_p for the fixed plate systems and 215 kWh/kW_p for the tracker.

Technologies with the lowest MPP power temperature coefficients (P_{MPP}, %/K) have shown the highest normalised energy yields during the summer period with average energy yield of 557 kWh/kW_p on the dc side and 507 kWh/kW_p on the ac side. In addition, the higher output of the tracker system is far more pronounced during the summer. Conversely, for the winter months, the average energy dc output for all systems was 324 kWh/kW_p and 293 kWh/kW_p on the ac side (see Fig. 7). The energy variation was lower during the period of spring and autumn, as the normalised ac energy yields were 431 kWh/kW_p and 385 kWh/kW_p respectively, while on the dc side 474 kWh/kW_p and 423 kWh/kW_p.

The percentage deviation from the fixed plate normalised ac energy yield seasonal average and the outdoor measured MPP power temperature coefficient (P_{MPP}, %/K) are shown for each technology in Table 6.

Furthermore, the performance ratio (PR) which is an evaluation criterion of PV systems defined as the relationship between actual and nominal yield, was measured for all systems on the ac side within the range of 73–85%. In this particular comparison it was obvious that the PV systems with the highest energy yield also had the highest PR values (see Fig. 8).

Table 6
Percentage deviation from the normalised to nameplate (kW_p) seasonal average ac energy yield and outdoor measured MPP power temperature coefficient (P_{MPP}, %/K) of the installed systems in Nicosia.

PV technology	Summer (%)	Autumn (%)	Winter (%)	Spring (%)	P_{MPP} (%/K)
Atersa mono-c-SI tracker	27.0	32.3	33.3	25.7	−0.56
Atersa mono-c-SI	−1.9	1.1	3.2	2.1	−0.56
BP mono-c-Si	−6.7	−9.5	−5.5	−7.7	−0.53
Sanyo HIT-Si	2.3	4.5	3.7	2.7	−0.42
Suntechnics mono-c-Si	4.2	7.5	9.9	8.1	−0.45
Schott MAIN-Si	−1.4	0.5	2.9	1.0	−0.50
Schott EFG-Si	−3.1	−1.1	1.0	−0.3	−0.42
SolarWorld multi-c-Si	−2.6	−1.1	2.0	0.7	−0.49
Solon multi-c-Si	−2.5	−0.9	−0.5	0.8	−0.40
Mitsubishi a-Si	5.9	1.6	−8.2	−4.5	−0.19
Schott Solar a-Si	−1.4	−9.2	−11.8	−8.0	−0.20
Würth CIGS	3.5	5.6	4.6	5.1	−0.42
First Solar CdTe	3.7	1.1	−1.5	−0.1	−0.22

4.3. Comparison of performance with Germany

The high potential of PV in Cyprus is obvious when comparing data between the two test sites. In Stuttgart the average annual yield was 1194 kWh/$kW_{p_{rated}}$ compared to 1580 kWh/$kW_{p_{rated}}$ in Nicosia. The difference between the best and the worst performing PV system is 15% in both countries relative to the average values (see Fig. 9) although it should be noted that the solar irradiation measured in Stuttgart during the period of June 2006–2007 was approximately 19% higher than the long term average irradiation of other years.

The systems installed in Nicosia have shown a lower average measured PR than in Stuttgart and this is mainly due to the higher temperatures that decrease the module efficiency (see Fig. 10).

Further comparisons have been performed on the installed inverters that are rated at a European Efficiency of 91.6% and that were typically oversized by 10% in order to utilise all the energy from the PV modules. The average annual outdoor inverter efficiency measured in Nicosia was 90.9% and in Stuttgart 89.8%. All the systems in Nicosia have demonstrated higher annual

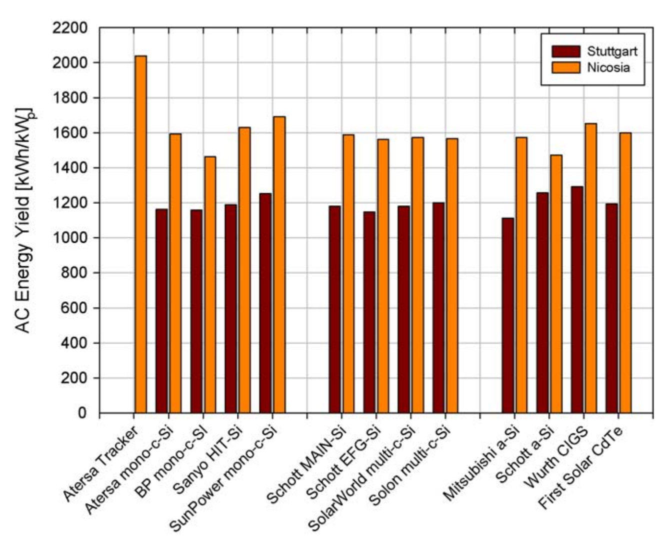

Fig. 9. Energy yield (ac) of the 12 fixed systems in Stuttgart and Nicosia in the time period June 2006–2007. The values are normalised to kW_p with the nameplate power.

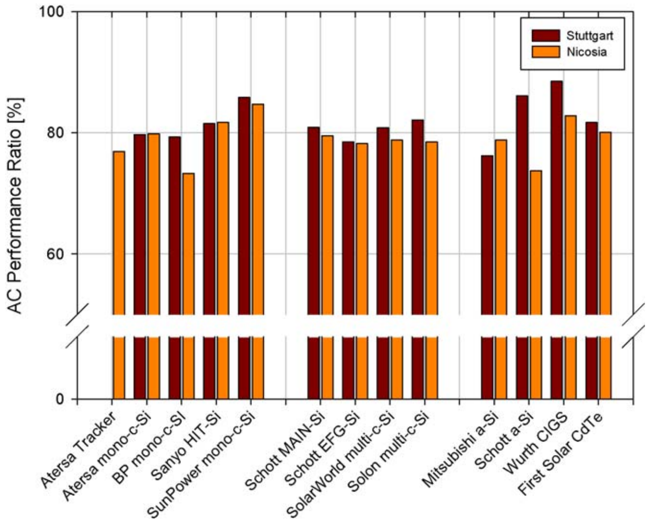

Fig. 10. Performance ratio (ac) of the installed systems in Nicosia and Stuttgart in the time period June 2006–2007.

inverter efficiencies than in Stuttgart, in the range of 0.7–1.4% which is attributed to the fact that a significantly lower share of inverter operation is at low power in Cyprus compared to Stuttgart [32]. The highest difference of 1.4% was observed for the installed Schott Solar MAIN multi-crystalline modules and the lowest difference of 0.7% for the Mitsubishi amorphous silicon modules.

In addition, the increased module temperature that is observed in Cyprus is an important loss mechanism especially near midday where module temperatures can exceed 60 °C (see Fig. 11).

5. PV potential in Cyprus

In general, a key benefit of PV technology in Cyprus is its ability to provide power to meet electricity peak demand. This important advantage of PV technology over other renewable energy technologies is illustrated through the comparison of PV electricity production and maximum electricity demand in Cyprus, which are shown to be directly in phase during the hot period (Fig. 12). In Cyprus, the highest load during the hot summer period is due to the increased operation of air conditioning systems. It is estimated that maximum demand and electricity consumption will increase in Cyprus mainly due to the expansion of building construction and this may accordingly lead to electricity tariffs that are more favourable for PV generation.

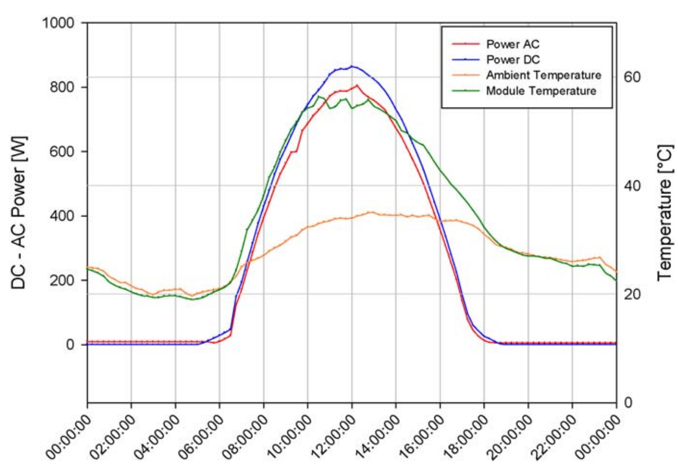

Fig. 11. Power (dc) and (ac), module backside and ambient temperature over the course of a sunny day in Cyprus (10th of August 2006) for PV system (Sanyo HIT).

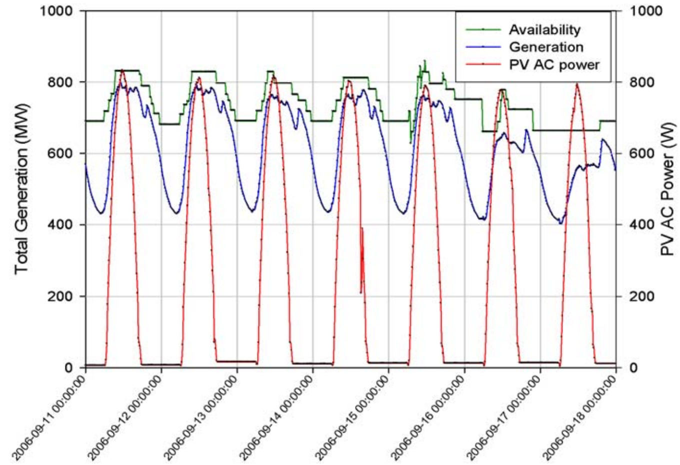

Fig. 12. Weekly variation of total generation (MW), availability (MW) and PV electricity generation (availability and generation data kindly made available by the Transmission System Operator (TSO)).

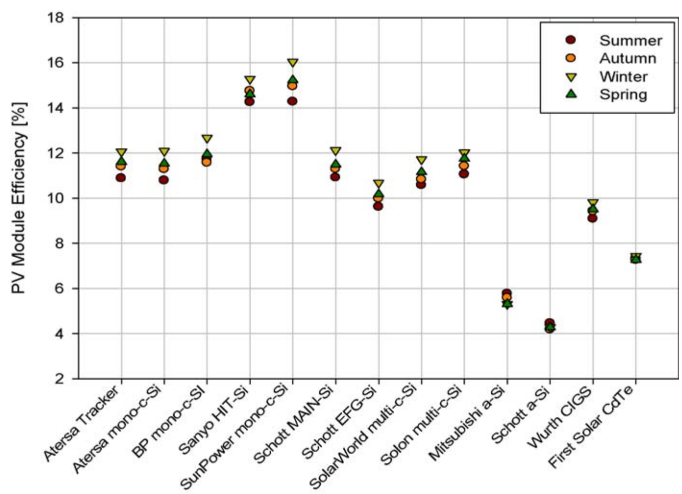

Fig. 13. Seasonal PV module efficiency for the systems installed in Nicosia, Cyprus (summer: 01/06/2006 to 31/08/2006, autumn: 01/09/2006 to 30/11/2006, winter: 01/12/2006 to 28/02/2007 and spring: 01/03/2007 to 31/05/2007).

The potential of thin film technologies in Cyprus has also been considered especially in accordance to the already expanding segment of BIPV. Thin films have been preferred over crystalline technologies to serve as building exteriors, as they can provide a better aesthetic appeal and have physical properties such as semi-transparency desirable for use in window, facade and other building elements. The evaluation of the thin film technologies in Cyprus has shown significant potential for the CIGS and CdTe as their energy yield over the evaluation period was higher than the amorphous silicon systems installed on site. Additional investigations on the seasonal efficiency variation of all technologies have shown that throughout the year, the outdoor efficiency of the thin film technologies is less affected compared to the crystalline silicon technologies (see Fig. 13).

6. Conclusion

The emergence and rapid expansion of different PV technologies have highlighted the potential of PV to become one of the world's leading energy sources. A key parameter in the successful integration of different photovoltaic technologies is good

knowledge of their performance and potential under the climatological conditions of any particular location.

The outdoor evaluation results clearly show that the high energy yield, within the range of 1600–1700 kWh/kW$_p$ and performance results of the different PV systems installed in Cyprus compared to the same systems in Stuttgart, provide strong evidence that such technologies can have a major impact on the future energy mix of countries with a high solar resource. In the hot climate of Cyprus, highest annual energy yields have been produced by technologies with the lowest outdoor measured P_{MPP} temperature coefficients highlighting the importance of the temperature loss parameter in hot climates. On a seasonal basis the efficiency variation measured for all technologies has shown that throughout the year, thin film technologies retain a more stable efficiency compared to the crystalline silicon technologies. Finally, the measured high DNI component (over 70% of the global irradiance) is another strong proof for the suitability of CPV in the Mediterranean region.

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